

**THE  $t\bar{t}$  ASYMMETRY IN THE STANDARD MODEL AND BEYOND**

Germán Rodrigo

*Instituto de Física Corpuscular, UVEG - Consejo Superior de Investigaciones Científicas,  
Parc Científic, 46980 Paterna (Valencia), Spain*

A sizable charge asymmetry in top quark pair production has been observed at the Tevatron. The experimental results seem to exceed systematically the Standard Model theory predictions by a significant amount and have triggered a large number of suggestions for 'new physics'. The effect is also visible at the LHC, and preliminary results have already been presented by the ATLAS and CMS collaborations. In this talk, we review the present status of the theoretical predictions, and their comparison with the experimental measurements.

**1 Introduction**

Top quark production at hadron colliders is one of the most active fields of current theoretical and experimental studies<sup>1</sup>, and one of the most promising probe of physics beyond the Standard Model (SM). Since 2007, sizable differences have been observed between theory predictions<sup>2,3,4,5</sup> for the top quark charge asymmetry and measurements by the CDF<sup>6,7,8</sup> and the D0<sup>9,10,11</sup> collaborations at the Tevatron. This discrepancy was particularly pronounced for the subsample of  $t\bar{t}$  pairs with large invariant mass,  $m_{t\bar{t}} > 450$  GeV, and the asymmetry defined in the  $t\bar{t}$  rest-frame, where a  $3.4\sigma$  effect was claimed<sup>6</sup>, although recent CDF analysis<sup>12</sup> lower this discrepancy in the large invariant mass region to less than  $3\sigma$ . D0 also finds a  $3\sigma$  discrepancy when the asymmetry is defined in the leptonic decaying products<sup>9</sup>. It is interesting to note that both experiments find systematically a positive excess with respect to the SM.

These discrepancies have triggered a large number of theoretical investigations, using these results, either to restrict new physics like heavy axigluons<sup>13,14</sup> or Kaluza-Klein gluons<sup>15</sup> or to postulate a variety of new phenomena in the t-channel (u-channel)<sup>16,17,18</sup>. At the same time, the robustness of the leading order QCD prediction has been studied in<sup>19,20</sup>, where it has been argued that next-to-leading (NLL) as well as next-to-next-to-leading (NNLL) logarithmic corrections do not significantly modify the leading order result, in agreement with the approach advocated in<sup>3,4</sup> (Note, however, the large corrections observed for the corresponding studies of the  $t\bar{t}$ +jet sample<sup>21</sup>).

More recently, also the CMS<sup>22,23,24</sup> and ATLAS<sup>25</sup> collaborations have presented the first measurements of the top quark charge asymmetry at the LHC. Although the experimental errors are still large, both experiments find central values that lie below the SM prediction<sup>26</sup>, in contrast with the Tevatron results. Other measurements at the LHC are also heavily constraining the parameter space of the models that have been advocated to explain the excess on the charge asymmetry at the Tevatron.

In this talk we revisit the SM prediction of the top quark charge asymmetry at the Tevatron and the LHC<sup>26</sup>. We summarize the experimental measurements of the asymmetry and update

the pull of their discrepancy with the SM. We introduce a new quantity  $A_{t\bar{t}}(Y)$ , which measures the charge asymmetry with respect to the average rapidity of top and antitop quarks, being a suitable observable both at the Tevatron and the LHC. We also analyze the effect of introducing a cut in the  $t\bar{t}$  transverse momentum as a possible explanation of the discrepancy. Finally, we comment on beyond the SM contributions to the asymmetry

## 2 The charge asymmetry in the SM

The dominant contribution to the charge asymmetry originates from  $q\bar{q}$  annihilation<sup>3,4</sup>. Specifically, it originates from the interference between the Born amplitudes for  $q\bar{q} \rightarrow Q\bar{Q}$  and the part of the one-loop correction, which is antisymmetric under the exchange of the heavy quark and antiquark (box and crossed box). To compensate the infrared divergences, this virtual correction must be combined with the interference between initial and final state radiation. Diagrams with triple gluon coupling in both real and virtual corrections give rise to symmetric amplitudes and can be ignored. The corresponding contribution to the rate is conveniently expressed by the absorptive contributions (cuts) of the diagrams depicted in Fig 1. A second contribution to the asymmetry from quark-gluon scattering (“flavor excitation”) hardly contributes to the asymmetry at the Tevatron. At the LHC, it enhances the asymmetry in suitable chosen kinematical regions<sup>4</sup>. CP violation arising from electric or chromoelectric dipole moments of the top quark do not contribute to the asymmetry, unless the asymmetry is defined through the decay products.

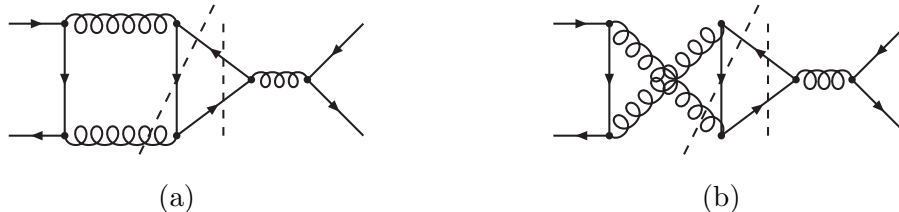


Figure 1: Cut diagrams representing the QCD contribution to the charge asymmetry.

The inclusive charge asymmetry is proportional to the symmetric colour factor  $d_{abc}^2 = 40/3$ , and it is positive, namely the top quarks are preferentially emitted in the direction of the incoming quarks at the partonic level<sup>3,4</sup>. The colour factor can be understood from the different behaviour under charge conjugation of the scattering amplitudes with the top and antitop quark pair in a colour singlet or colour octet state. The positivity of the inclusive asymmetry is a consequence of the fact that the system will be less perturbed, or in other words will require less energy, if the outgoing colour field flows in the same direction as the incoming colour field. On the other hand, radiation of gluons requires to decelerate the colour charges, and thus the asymmetry of the  $t\bar{t}$ +jet sample is negative.

At Tevatron, the charge asymmetry is equivalent to a forward-backward asymmetry as a consequence of charge conjugation symmetry, and thus top quarks are preferentially emitted in the direction of the incoming protons. The charge asymmetry can also be investigated in proton-proton collisions at the LHC<sup>2,3,4</sup> by exploiting the small  $t\bar{t}$  sample produced in annihilation of valence quarks and antiquarks from the sea. Since valence quarks carry on average more momentum than sea antiquarks, production of top quarks with larger rapidities will be preferred in the SM, and antitop quarks will be produced more frequently at smaller rapidities. Figure 2 shows for comparison, qualitatively and not to scale, the rapidity distributions of the top and the antitop quarks at the Tevatron (left) and the LHC (right).

Diagrams similar to those depicted in Fig. 1, where one of the gluons has been substituted by a photon, also lead to a contribution to the charge asymmetry from mixed QED-QCD cor-

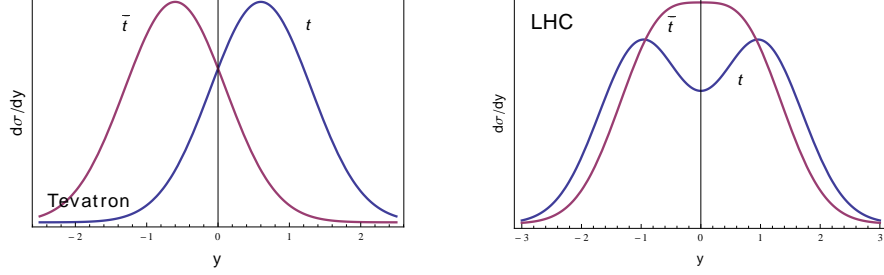


Figure 2: Not to scale rapidity distributions of top and antitop quarks at the Tevatron (left) and the LHC (right).

rections. The relative factor between QCD and QED asymmetries amounts to

$$f_q^{\text{QED}} = 3 \frac{\alpha_{\text{QED}} Q_t Q_q}{\frac{\alpha_S}{2} \left( \frac{d_{abc}^2}{4} \right)^2} = \frac{\alpha_{\text{QED}}}{\alpha_S} \frac{36}{5} Q_t Q_q \quad (1)$$

for one quark species, and to

$$f^{\text{QED}} = \frac{4f_u^{\text{QED}} + f_d^{\text{QED}}}{5} = \frac{\alpha_{\text{QED}}}{\alpha_S} \frac{56}{25} \approx 0.18, \quad (2)$$

after convolution with the PDFs if one considers as a first approximation that the relative importance of  $u\bar{u}$  versus  $d\bar{d}$  annihilation at the Tevatron is 4 : 1. Thus, to an enhancement of nearly twenty percent of the QCD asymmetry, in good agreement with the more detailed numerical studies of<sup>26,27</sup>. At the LHC, the relative importance of  $u\bar{u}$  versus  $d\bar{d}$  annihilation is approximately 2 : 1, thus reducing  $f^{\text{QED}}$  down to 0.13. Similarly, weak contributions with the photon replaced by the Z boson should be considered at the same footing. However, as a consequence of the cancellation between up and down quark contributions, and the smallness of the weak coupling, the weak corrections at the Tevatron are smaller by more than a factor 10 than the corresponding QED result. For proton-proton collisions the cancellation between up and down quark contributions is even stronger and the total weak correction is completely negligible.

### 3 SM predictions of the charge asymmetry at the Tevatron and the LHC

The charge asymmetry at the Tevatron is equivalent to a forward-backward asymmetry. In the laboratory frame it is given by either of the following definitions

$$A_{\text{lab}} = \frac{N(y_t > 0) - N(y_t < 0)}{N(y_t > 0) + N(y_t < 0)} = \frac{N(y_t > 0) - N(y_{\bar{t}} > 0)}{N(y_t > 0) + N(y_{\bar{t}} > 0)}, \quad (3)$$

requiring to measure the rapidity of either the  $t$  or the  $\bar{t}$  for each event. The most recent experimental analysis measure both rapidities simultaneously, and define the asymmetry in the variable  $\Delta y = y_t - y_{\bar{t}}$ , which is invariant under boosts, and thus equivalent to measure the charge asymmetry in the  $t\bar{t}$  rest-frame:

$$A_{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}. \quad (4)$$

The size of the charge asymmetry in the  $t\bar{t}$  rest-frame is about 50% larger than in the laboratory frame<sup>2</sup> because part of the asymmetry is washed out by the boost from the partonic rest-frame to the laboratory.

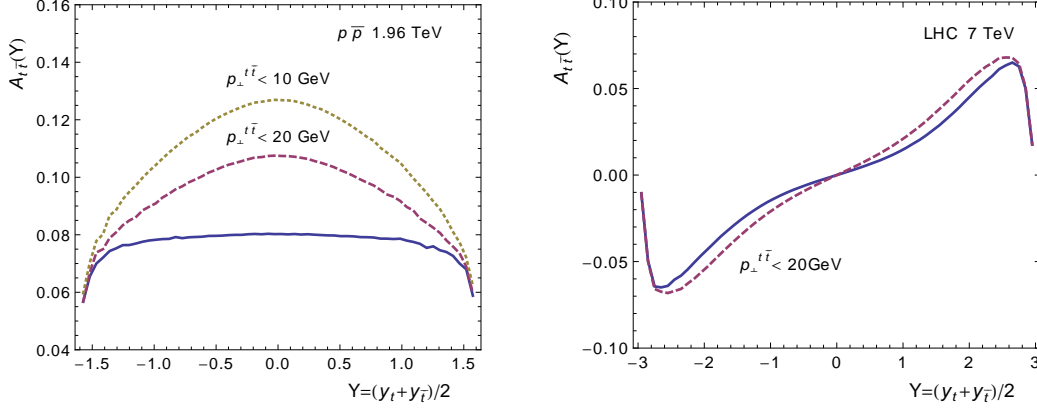


Figure 3: Universal charge asymmetry  $A_{t\bar{t}}(Y)$  as a function of the mean rapidity  $Y = (y_t + y_{\bar{t}})/2$ . Solid line: without cut on  $p_{\perp}^{t\bar{t}}$ , dotted/dashed lines: with cut on  $p_{\perp}^{t\bar{t}}$ .

At the LHC, the charge asymmetry has been defined<sup>23,25</sup> through  $\Delta|y| = |y_t| - |y_{\bar{t}}|^a$

$$A_C^y = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}. \quad (5)$$

A forward–backward asymmetry obviously vanishes in a symmetric machine like the LHC.

The  $t\bar{t}$  asymmetry is thus often called forward–backward asymmetry at the Tevatron and charge asymmetry at the LHC, but in fact, although the kinematical configurations of the two machines are different the physical origin of the asymmetry in both cases is the same (see Fig. 1). However, it is possible to define a universal observable, namely an asymmetry suitable for both the Tevatron and the LHC, if we measure the charge asymmetry with respect to the average rapidity  $Y = (y_t + y_{\bar{t}})/2$  of the top and the antitop quarks. This universal charge asymmetry<sup>26</sup> is obtained by selecting events for a definite average rapidity  $Y$  and calculating their asymmetry as in Eq. (4):

$$A_{t\bar{t}}(Y) = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}. \quad (6)$$

The theoretical prediction for the differential distribution  $A_{t\bar{t}}(Y)$  as a function of  $Y$  is shown in Fig. 3 (left) for the Tevatron, and in Fig. 3 (right) for the LHC. By construction  $A_{t\bar{t}}(Y)$  is a symmetric function of  $Y$  at the Tevatron, and an antisymmetric function of  $Y$  at the LHC. At the Tevatron the asymmetry  $A_{t\bar{t}}(Y)$  is almost flat, at the LHC it resembles a forward–backward asymmetry. The corresponding integrated asymmetries coincide with the usual charge asymmetry in the  $t\bar{t}$  rest-frame from Eq. (4),  $A_{t\bar{t}}(Y) \rightarrow A_{t\bar{t}}$ , and with the charge asymmetry  $A_C^y$  in Eq. (5) if we select events with  $Y$  either positive or negative. The advantage of Eq. (6) for the LHC is that the size of the asymmetry can be enhanced by selecting events with a minimum average rapidity  $Y > Y_{\text{cut}}$ <sup>26</sup>. This is relevant because  $t\bar{t}$  production at the LHC, contrary to what happens at the Tevatron, is dominated by gluon fusion which is symmetric. Therefore, in order to reach a sizable asymmetry at the LHC it is necessary to introduce selection cuts to suppress as much as possible the contribution of gluon fusion events, and to enrich the sample with  $q\bar{q}$  events. In particular, gluon fusion is dominant in the central region and can be suppressed by introducing a cut in the average rapidity  $Y$  (or selecting events with large  $m_{t\bar{t}}$ ). Obviously this is done at the price of lowering the statistics, which, however, is not a problem at the LHC.

<sup>a</sup>CMS<sup>23</sup> has also used pseudorapidities to define the charge asymmetry with  $\Delta|\eta| = |\eta_t| - |\eta_{\bar{t}}|$ . The size of the asymmetry in  $\Delta|\eta|$  is only slightly higher<sup>26</sup> than with  $\Delta|y|$ .

Table 1: SM asymmetries in the laboratory  $A_{\text{lab}}$  and the  $t\bar{t}$  rest-frame  $A_{t\bar{t}}$  at Tevatron. Predictions are given also for samples with the top quark pair invariant mass  $m_{t\bar{t}}$  above and below 450 GeV, and with  $|\Delta y| = |y_t - y_{\bar{t}}|$  larger or smaller than one. Summary of latest experimental results: numbers with \* refer to "reconstruction level", the others to parton level. The former cannot be compared directly with the quoted theoretical predictions.

Tevatron	inclusive	$m_{t\bar{t}} < 450$ GeV	$m_{t\bar{t}} > 450$ GeV	$ \Delta y  < 1$	$ \Delta y  > 1$
SM laboratory $A_{\text{lab}}$	0.056 (7)	0.029 (2)	0.102 (9)		
CDF <sup>6</sup>	0.150 (55)	0.059 (34)*	0.103 (49)*		
SM $t\bar{t}$ rest-frame $A_{t\bar{t}}$	0.087 (10)	0.062 (4)	0.128 (11)	0.057 (4)	0.193 (15)
D0 <sup>9</sup>	0.196 (65)	0.078 (48)*	0.115 (60)*	0.061 (41)*	0.213 (97)*
CDF <sup>12</sup>	0.162 (47)	0.078 (54)	0.296 (67)	0.088 (47)	0.433 (109)

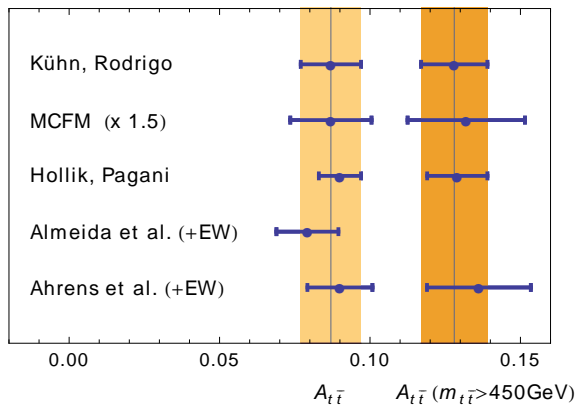


Figure 4: Summary of theoretical predictions for the inclusive charge asymmetry at the Tevatron in the  $t\bar{t}$  rest-frame,  $A_{t\bar{t}}$ , and in the large invariant mass region  $A_{t\bar{t}}(m_{t\bar{t}} > 450\text{GeV})$ .

Predictions in the SM for the charge asymmetry at the Tevatron in the laboratory frame and in the  $t\bar{t}$  rest-frame are listed<sup>26</sup> in Table 1. In order to compare theoretical results in the SM with the most recent measurements at Tevatron, predictions in Table 1 are presented also for samples with  $m_{t\bar{t}}$  larger and smaller than 450 GeV, and with  $|\Delta y| = |y_t - y_{\bar{t}}|$  larger and smaller than one. These predictions include also the QED and weak (strongly suppressed) corrections. Those corrections enhance the QCD asymmetry by an overall factor 1.21, which is slightly different from Eq. (2) due to the deviation of the relative amount of  $u\bar{u}$  and  $d\bar{d}$  contributions from the simple approximation 4 : 1.

The charge asymmetry is the ratio of the antisymmetric cross-section to the symmetric cross-section. The leading order contribution to the antisymmetric cross-section is a loop effect (Fig. 1), but the leading order contribution to the symmetric cross-section appears at the tree-level. This suggest that the charge asymmetry should be normalized to the Born cross-section<sup>3,4</sup>, and not the NLO cross-section<sup>6</sup>, in spite of the fact that the later is well known, and is included in several Monte Carlo event generators such as MCFM<sup>28</sup>. This procedure<sup>3,4</sup> is furthermore supported by the fact that theoretical predictions resumming leading logarithms (NLL<sup>19</sup> and NNLL<sup>20</sup>) do not modify significantly the central prediction for the asymmetry.

Figure 4 summarizes the state-of-the-art SM predictions for the inclusive asymmetry in the  $t\bar{t}$  rest-frame, and in the large invariant mass region,  $m_{t\bar{t}} > 450$  GeV, from different authors<sup>26,6,27,19,20</sup>. In order to have a coherent picture, EW corrections have been added to the predictions presented in<sup>6,19,20</sup>, which amount to a factor of about 1.2, and the Monte Carlo based prediction has also been corrected by an extra factor of 1.3 to account for the normal-

Table 2: SM charge asymmetries  $A_C^y$ , and integrated universal charge asymmetry  $A_{t\bar{t}}^{\text{cut}}(Y_{\text{cut}} = 0.7)$ , at different LHC energies. Summary of recent measurements by CMS and ATLAS.

	$A_C^y$	$A_{t\bar{t}}^{\text{cut}}(Y_{\text{cut}} = 0.7)$
LHC 7 TeV	0.0115 (6)	0.0203 (8)
LHC 8 TeV	0.0102 (5)	0.0178 (6)
LHC 14 TeV	0.0059 (3)	0.0100 (4)
LHC 7 TeV CMS <sup>22</sup>	0.004 ± 0.010 ± 0.012	
LHC 7 TeV ATLAS <sup>25</sup>		
	-0.018 ± 0.028 ± 0.023	

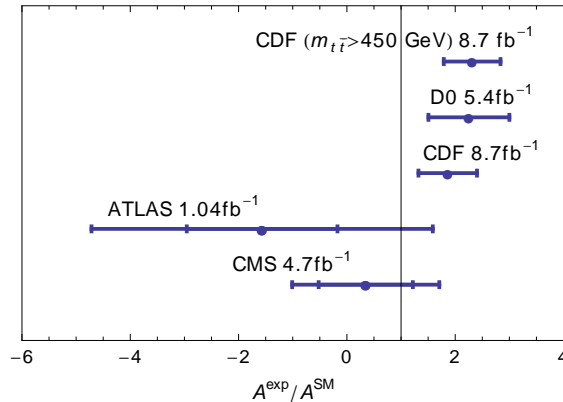


Figure 5: Comparison of some of the most recent measurements of the charge asymmetry at the Tevatron and the LHC with the corresponding SM predictions.

ization to the NLO cross-section. A nice agreement is found among the different theoretical predictions.

There is, moreover, an intense effort in the community to evaluate the  $t\bar{t}$  cross-section at the next-to-next-to-leading order (NNLO)<sup>31,32</sup>. First results have been obtained recently for the channel  $q\bar{q} \rightarrow t\bar{t}$ <sup>33</sup>. Thus, all the relevant ingredients to calculate the asymmetry at the next order are available; NNLO corrections to the gluon fusion channel are not necessary if the asymmetry is normalized to the NLO cross-section.

The SM predictions for the charge asymmetry  $A_C^y$  in Eq. (5) are listed in Table 2 for different center-of-mass energies of the LHC, together with the most recent experimental measurements at  $\sqrt{s} = 7$  TeV. It is interesting to note that both experiments obtain central values for the asymmetry that are below the SM prediction. These results, although compatible with the SM prediction within uncertainties, are in some "tension" with the Tevatron measurements. Unless different selection cuts are introduced, the signs of the asymmetry at the Tevatron and the LHC are generally correlated. A quantitative estimation of this "tension" is shown in Fig. 5. It amounts to about  $1\sigma$  or below, and thus it is still non conclusive. New analysis with larger statistics should be expected soon, and will reduce further the experimental errors. In fact, given the amount of data expected to be collected in the current 2012 run of the LHC, the measurements of the asymmetry will become soon dominated by systematics, and not by statistics as for the Tevatron.

Unfortunately, the asymmetry at the LHC decreases at higher energies because of the larger gluon fusion contribution. It can, however, be enhanced by selecting events with large rapidities or large  $m_{t\bar{t}}$ . Theoretical predictions for the universal charge asymmetry in Eq. (6) with  $Y > 0.7$  are also presented in Table 2.

## 4 Explaining the discrepancy with the SM

In the last years, hundreds of papers have postulated new physics models to explain the discrepancy with the SM, particularly after the publication of the CDF measurement in the high invariant mass region<sup>6</sup>. A new CDF measurements with larger statistics<sup>12</sup> define better the slope of the  $m_{t\bar{t}}$  distribution, showing a persistent depart from the SM, although slightly reducing the discrepancy. Although smaller than measured, the SM definitely predicts a positive slope in the  $m_{t\bar{t}}$  distribution. This effect can be understood from the fact that events with real emission of gluons give a negative contribution to the asymmetry, and from the fact that  $m_{t\bar{t}} < \sqrt{\hat{s}}$ , where  $\hat{s}$  is the partonic center-of-mass energy of each event. As a consequence, negative contributions to the asymmetry prefer to be at low values of  $m_{t\bar{t}}$ , while the high invariant mass region receives less bremsstrahlung contributions. D0<sup>9</sup> also shows results which are consistent with CDF. Thus, CDF and D0 analysis with full statistics or the combination of both experiments will provide more accurate results in the future but it is unlikely that the new measurements will differ significantly with previous results.

There has been a recent discussion about the distribution of the transverse momentum of the  $t\bar{t}$  pair<sup>26,9,12,29</sup>,  $p_{\perp}^{t\bar{t}}$ . An inaccurate simulation of the  $p_{\perp}^{t\bar{t}}$  distribution could lead to a mismatch in the estimate of the negative contributions to the asymmetry, and thus to an asymmetry much larger than expected. On the other hand, it has also been suggested that the  $p_{\perp}^{t\bar{t}}$  distribution could be used to enhance the size of the asymmetry<sup>30</sup>. In that case theoretical prediction might be affected by large  $\ln(p_{\perp}^{t\bar{t}})$  that need to be resummed. This issues should be further investigated.

Since the asymmetry is proportional to the strong coupling  $\alpha_S(\mu)$  a larger asymmetry can be obtained by conveniently choosing a very small value of the renormalization scale<sup>34</sup>. However, a fine tuning of  $\alpha_S(\mu)$  does not guarantee the convergence of the perturbative series at higher orders, and would bring the LHC results in disagreement with the SM.

It is not the purpose of this talk to make a complete review of new physics models explaining the Tevatron anomaly on the charge asymmetry. It is, however, interesting to mention that new LHC results, not only on direct searches in the dijet or  $t\bar{t}$  differential cross-sections, but also in same-sign top quark production<sup>35</sup>, or  $t\bar{t}$ +jet<sup>36</sup>, are seriously constraining the parameter space of these models.

## 5 Summary

Tevatron has shown in the last years a systematic upward discrepancy in the measurement of the top quark charge asymmetry with respect to theoretical predictions in the SM. These discrepancies have triggered a large number of theoretical speculations about possible contributions beyond the SM. The LHC experiments have also presented the first measurements of the charge asymmetry, and due to his present good performance, will be able to provide much more accurate and competitive measurements after the 2012 run. New theoretical developments should also help to shed light on the Tevatron anomaly. Certainly, 2012 will be a crucial date to solve this puzzle.

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